NANOSECOND-CURRENT PROBE FOR HIGH VOLTAGE EXPERIMENTS*

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Abstract

A current probe has been designed which allows measurement of ns-pulsed currents in high voltage environments. The probe consists of a current transformer and an optical transducer. The transformer coil in a metallic torus is considered as a slow-wave transmission line and is terminated with its wave impedance. In this mode of operation current pulses shorter than twice the transit time of the transmission line are linearly transformed. The voltage gain of the transformer is considerably greater than that of commonly used self integrating Rogowski-coils. The signal current drives a light emitting diode, with an impedance negligible compared to the wave impedance. The emitter is optically coupled to a photodiode, thus isolating the recording system from the pulsed power experiment. The probe, as used has a linear response for pulses shorter than about 400 ns and currents of > 1 A. The risetime is less than 5 ns.

Introduction

Rogowski coils are commonly used for current measurement in pulsed power experiments. For pulses in the ns range such coils have to be considered as slow wave transmission lines with distributed voltage sources due to flux changes Φ in the coil[1,2,3]. These transmission lines are usually operated in the so-called self-integrating mode, with a terminating resistor R which is small compared to the impedance of the line. The risetime, which can be achieved by using such a self-integrating current probe is in the order of ns. The response is linear for times short compared to the characteristic time L/R where L is the inductance of the coil[2].

The sensitivity of the self-integrating Rogowski coil is approximately R/N, where N is the number of turns. Thus, increasing the characteristic time L/R lowers the sensitivity, which is generally in the order of several 10^{-3} V/A[4]. The self-integrating coil, therefore is useful only for high current experiments. For currents less than 100 A, with 1 A resolution, characteristic signals are in the mV range and therefore susceptible to noise.

The sensitivity can be increased considerably by terminating the line with a resistor which equals the wave impedance. The response however, then only is linear for twice the transit time. With transit times which are usually in the order of 10 ns the matched probe was not seen as a competitor for the self integrating Rogowski coil. The transit time, however, can be increased drastically by taking a transmission line parameter into account which was not considered as being important so far: the distributed capacitance C'. By constructing the slow wave structure in a way that C' becomes very large (nF) it is possible to obtain a probe with almost optimum sensitivity and strictly linear response for pulse durations of up to several µs.

The high sensitivity of the probe allows use of a low cost optical transducer system for electrical isolation against voltages of several 100 kV in pulsed power systems. The system, consisting of a slow wave structure current probe driving a light emitting diode, which is optically coupled to a photodiode, has a sensitivity of several mV/A and a risetime of 3 ns. It is suitable for measuring currents with amplitudes > 1 A and a duration of up to several µs with reduced or eliminated influence of noise.

Current Probe

The design of the current probe is shown in Fig. 1a. It consists of an N-turn coil with rectangular cross-section (sides a and b), and major radius R in a metallic torus with a slit along the inner circumference. The coil and the surrounding electrostatic shield act as a slow wave structure with a characteristic impedance $Z_0 = (L'/C')^{1/2}$ and propagation velocity $v = (L'C')^{-1/2}$, where L' and C' are the inductance and capacitance per unit length. The distance between the coil as an inner conductor and the housing as an outer conductor of the transmission line is minimized to provide a large value of C'. One end of the coil is shorted (coil connected to shield) and the output is matched with $R = Z_0$.

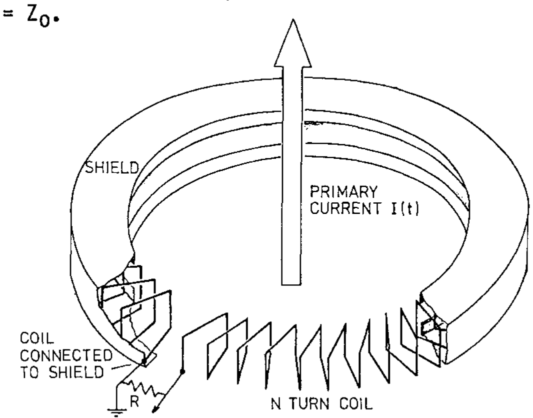

Fig 1a Geometry of the current probe

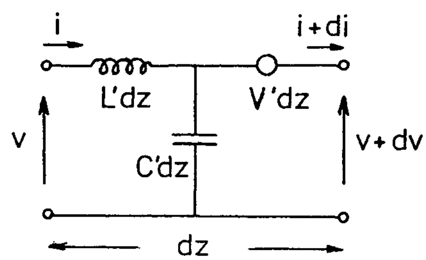

Fig 1b Equivalent circuit

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14. ABSTRACT
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The induced voltage per length dz of the circumference is given by Faraday's Law (for R>>a,b) as a function of the time derivative of the measured current I:

$$V_{ind,dz} = -N \frac{\mu_0}{(2\pi R)^2} (ab) \frac{dI}{dt} dz$$

and acts as a source voltage for an equivalent circuit element[3] of length dz (Fig 1b). The wave equation for the probe current i(z,t) in this case, using $L' \simeq \mu_0 N^2/(2\pi R)^2(ab)$, is

$$\frac{\partial^2 i}{\partial t^2} - \frac{1}{L'C'} \frac{\partial^2 i}{\partial z^2} = \frac{1}{N} \frac{d^2 I}{dt^2}$$

with the solution for the output current

$$i_{out}(t) = i(z = 2\pi R, t) = \frac{1}{2N} (I(t) - I(t-2T))$$

where T denotes the coil transit time ($T = 2\pi R/v$). Thus, for currents I(t) with a duration < 2T, the term I(t-2T) is zero and the output current is 1/2N times the current to be measured.

Optical Transducer

Fig 2a shows the electrical circuits for the emitter, a laser diode (type LCW-10, M/A-Com Laser Diode Inc.) and the receiver (photodiode S1188, Hamamatsu). The emitting diode is biased with a forward current of 75 mA to the center of the approximately linear part of the power vs. current characteristics above threshold. This bias provides a linear transfer of negative and positive input signals up to a maximum amplitude of 10 mA (Fig 2b). The diode has been matched to 50 Ω, and limits the useful range of primary currents to $-8A < I < +8A$ for test measurements.For higher currents, the probe output signal has to be attenuated to the linear transferred input current range of the laser diode. The emitted light is focused on the entrance of a quartz fiber (diameter 600 µm, length 10 m) connected to the receiver. The amplitude transfer characteristic of the transducer system is shown in Fig. 2b. Its risetime of 3 ns is mainly determined by dispersion in the fiber.

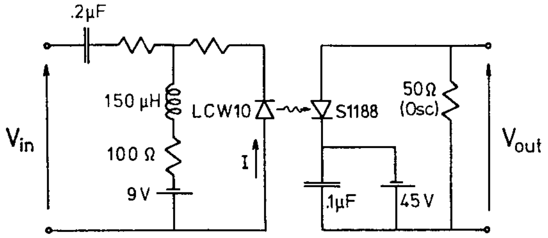

Fig 2a Optical transducer setup

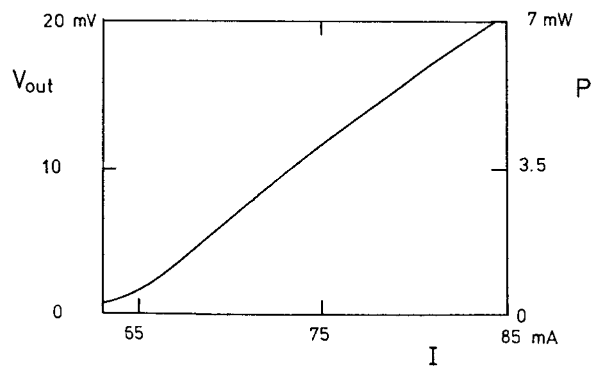

Fig 2b Transfer characteristics of the optical transducer

Results of Test Measurements

A probe with parameters given in Table 1 has been tested in a matched 50 Ω coaxial cavity with inner radius 4.4 cm, and outer radius 10.2 cm, by applying a rectangular input pulse of variable duration (Fig. 3a). The output signal of the probe is divided to show both the probe response directly and the output pulse transfered by the optical transducer. Fig. 3b shows the leading pulse edges, Fig. 3c shows the test results for an input pulse of 400 ns duration. This time is approximately 2/3 of the linearly transferred primary current duration of 2T = 580 ns. Probe responses to pulses with durations approaching twice the transit time show increasing oscillations, which are probably due to dispersive signal distortions in the slow wave transmission line. This dispersion, limiting the useful time range, is caused by the finite, frequency dependent skin resistance of the coil and by the periodic variation of the line impedance due to the slit in the inner circumference of the shield.

N	(number of turns)	:	400
R	(major radius)	:	8.7 cm
a=b	(sides of cross section)	:	1.06 cm
L'	(inductance per unit length)	:	1.518 µH/cm
C'	(capacitance per unit length)	:	19.2 pF/cm
Z_0	(characteristic impedance)	:	280 Ω
v	(propagation velocity)	:	1.9×10^8 cm/s
T	(Transit time)	:	290 ns
R_W	(wire resistance)	:	1.8 Ω
R/2N	(sensitivity)	:	.35 V/A

Table 1 Probe parameters

Summary

With transmission line type current sensors, matched with the line impedance, sensitivities of up to 1 V/A can be obtained. This is particularly important for low current e-beam devices or pulsed power experiments where sensor and recording system are coupled though optical links with current driven laser diodes as emitters. The measurement time range of these sensors is mainly determined by dispersion effects which limit the application to pulses with duration smaller than several microseconds.

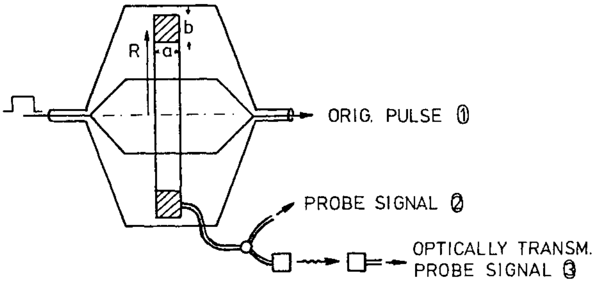

Fig 3a   Test setup

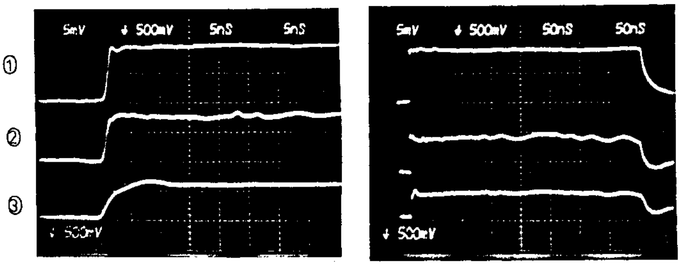

Fig 3b, c   upper trace: input pulse
             center trace: probe output
             lower trace: transducer output

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